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EFFECTS OF WOODY VEGETATION ON LEVEE INTEGRITY DURING FULL SCALE TESTING AT TWITCHELL ISLAND IN RIO VISTA, CALIFORNIA

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ABSTRACT

This paper summarizes the second in a series of two infiltration experiments investigating the effects of woody vegetation on levee integrity. The test site was located along the crown of a bypassed levee along an oxbow segment of the Sevenmile slough on Twitchell Island in Rio Vista, California. The study involved construction of an 8 ft deep crown trench extending through the root system of a landside live oak tree, and a waterside valley oak tree. A control trench was constructed along a segment without large trees. During the test, the crown trench was flooded and maintained at constant head to simulate a flood condition with water delivered from the center of the levee rather than the side. Piezometers and tensiometers were installed to measure positive and negative pore water pressures, respectively, within the zone of flow to describe the wetting and flow patterns as they evolved within the levee. Burrow networks, fracturing, and voids within levee soils, as well as variability of stratigraphic conditions across the site added complexity. Extensive burrowing activity likely associated with muskrats, pocket gophers, and voles affected flow patterns. Visual observations were made during the flow test to view surficial seepage and flow patterns from the surface while subsurface instruments were continuously monitored. The present levee appears to have been founded on older, overbank deposits comprised of lower permeability soils than the overlying levee fill. Water appeared to accumulate on this stratigraphic layer, driving seepage patterns. Cracking was observed in the crown road along the levee crest within the first 24 hours of the flow test. After approximately 40 hours of flow, the waterside oak tree, initially leaning at an angle of approximately 43 degrees from horizontal, rotated an additional approximately 20 degrees into the slough, creating cracks and deformation along the waterside slope. Ground-based tripod light detection and ranging (T-LiDAR) was used to complement our efforts related to tracking deformations during the test. Computer modeling is used as a tool to better understand flow patterns, observed cracking, and the role of landside and waterside trees in stability of the studied levee. Based on calibrated numerical simulations, trees were found not to play a significant role in seepage-induced rotational or block failure of the levee slopes. Where trees exhibit significant lean (center of mass extends beyond the fulcrum of the root plate), horizontal roots extending into the levee may place additional loads on the levee embankment. Loading of this type can be incorporated into two dimensional slope stability analyses, using mass-averaging to capture the three-dimensional impact of the tree. Tree overturning was evaluated at the waterside oak tree. Root forces were represented as a single horizontal force and a single vertical force. The method successfully captured the observed landside and waterside tree responses during the Crown Trench Seepage Test.

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INTRODUCTION
The devastating flooding of New Orleans resulting from Hurricane Katrina brought to light the fragility of levee systems across the United States. The years following this disaster have brought a renewed focus on public safety and a closer look at policies, standards, and conditions of existing levee systems.

In 2009, the United States Army Corps of Engineers (USACE) released the document “Guidelines for Landscape Planting and Vegetation Management at Levees, Floodwalls, Embankment Dams, and Appurtenant Structures”, ETL 1110-2-571, and recently released an update with minor changes (USACE, 2014). The guidelines show a vegetation-free zone across the levee surface and extending 15 feet from the toe of both the land and water sides (Figure 1). The vegetation-free zone is expanded where stability berms or other structures are present near the toe. This policy has been the subject of debate in states where levees were built close to adjacent to the rivers and as a result critical riverine habitat shares space with structures providing flood protection (Harder et al., 2011).

Figure 1. USACE Vegetation-Free Zone (Source: USACE ETL 1110-2-571).
Consensus has not been reached with regard to the impact of woody vegetation on levee integrity (Corcoran et al., 2010). Trees and their roots have been suggested to possibly undermine the integrity of compacted earthen levees by providing enhanced and focused seepage through the levees. Alternately, live tree roots are believed to strengthen the levee and improve slope stability in many cases (e.g., Shields and Gray, 1992; Ziemer, 1981). It is not known whether the documented benefits of roots in terms of reinforcing earth slopes and strengthening the slopes may more than offset the potentially damaging effects of any localized regions of higher pore water pressure within the levee. Shriro et al. (2011) explored the effects of live and decomposing tree roots on levee integrity through a full-scale levee seepage test, concluding that, under the studied conditions, voids created by decomposing roots were not sufficiently continuous and found animal burrows to control flow patterns during the test. This field test focuses on building upon results of Shriro et al. (2011) with a focus on live tree roots and achieving saturated conditions within the vicinity of the roots system.

**SUMMARY OF TWITCHELL ISLAND FIELD TEST**

The test was designed around the roots systems of two oak trees (both live) on the land and water sides of the south levee of the Sevenmile Slough (on the northern levee of Twitchell Island) in Rio Vista, California (Figure 2).
TEST LAYOUT AND DESCRIPTION
The concept of the Crown Trench Seepage Test involved excavation of an 8 foot deep and 2 foot wide trench through the levee crown and supplying the trench with water held at a constant head, simulating a flood condition where water is delivered from the center of the levee. Instrumentation installed within the zone of flow captured positive and negative pore water pressures before, during, and after flow. The as-built length of the control trench was approximately 31.5 feet while the as-built length of the tree trench was 95 feet with an approximate 5 foot separation between them. Water was pumped from the main channel of the slough and delivered to the trenches via gravity from a polyethylene reservoir (Figure 3).

An instrumentation layout was designed to monitor positive and negative pore water pressures in the vicinity of the landside and waterside oak trees and the control section. Sections A, B, and C represent the landside oak tree, the waterside oak tree and the control zones, the primary areas of study for this test. In the interest of evaluating the effect of distance from the tree center on seepage through a root system, supplemental instruments were placed at Lines D and E. Line D. Instruments consisted of vibrating wire piezometers and tensiometers with
electronic transducers as shown on Figure 4 and Figure 5. Instrumentation was placed in 6 rows with similar configuration at each primary line for ease of comparison, shown on interpreted stratigraphic sections (Figure 5). Interpreted sections were developed based on logged instrument holes, cone penetration test data, and historic topography, maps, and limited construction history.

Figure 3. Layout of Twitchell Island Crown Trench Seepage Test. Aerial photos (top) taken on May 19, 2012, capture the flow test setup.
Figure 4. Site and instrument layout plan showing instrument lines A through E.
Figure 5. Interpreted stratigraphic sections at instrument lines A, B, and C through the landside oak tree, the waterside oak tree, and the control section, respectively. Instrument rows 1 through 6 are shown.

The landside vegetation consisted primarily of low grass cover with patches of mowed and returning blackberry and included one oak tree, while the waterside was found to be densely vegetated (Figure 6 and Figure 7). Access to the waterside was limited due to dense vegetation, primarily of a blend of willow and elderberry as well as a small coastal live oak tree, and a large
60 year old waterside valley oak tree. Leaning at an angle of 46 degrees from the vertical. Dr. Dirk Van Vuren of UC Davis visited the site as the CLVRP team expert to evaluate the potential for burrowing mammals. Pocket gopher and vole activity were evident on the landside, while abandoned muskrat burrows were identified on the waterside.

Figure 6. Landside vegetation; views looking west (top) and north (bottom).

Figure 7. View of landside Coast live oak tree looking south (left) and waterside Valley oak tree looking north (center and right). Waterside Valley oak shows considerable lean, with a large branch extending out over the water (right).
TRENCH CONSTRUCTION AND FIELD LOGGING

The careful excavation and documentation of conditions within the control and tree trenches provided an important window into the heterogeneity of site conditions. Construction incorporated an excavator to construct the trench when roots were absent or scarce as well as an air knife to remove soils within root zones of the landside and waterside trees as discussed in Shriro (2014). Roots were sketched in three depth zones and branching direction was noted and used to estimate the origin of roots encountered (Figure 8). Landside burrowing activity was observed in the blackberry-laden areas north of the control instrument line (Line C) and around the landside oak tree (Figure 9). Roots were trimmed flush with sidewalls, soil stratigraphic conditions logged, burrows plugged to provide a cutoff from direct water infiltration, and the trench backfilled with pervious gravel prior to inundation with water.

Root area ratio in the trench near the waterside oak tree was extensive, especially at depths greater than 4 feet, while the landside oak tree root system was significantly less extensive (Figure 10). Tree species, age, and lean angle are likely contributing factors in these differences.
Figure 8. Roots at depths of 4 to 8 feet at Station TT 10 to 15.

Figure 9. Root and burrow log at depth of 6 to 8 feet at Stations 70-71. Live root growth in burrows of 2 to 3 ¼ inch diameter.

Figure 10. Root area ratio along the length of the control and tree trenches.

FLOW TEST
Instruments were calibrated and monitored and the flow test experiment was initiated by filling the levee crown trenches with water on May 21, 2012. The experiment ran for approximately 4
days in the tree trench before the water supply was turned off, while water was supplied to the control trench for 6 additional days (10 days total) to accommodate variability in instrument saturation (Figure 11).

Flows at the Twitchell Island test site were controlled by macroporosity and stratigraphic conditions related to the presence of natural, low permeability overbank deposits on which the existing levee was founded. Zones of macropores associated with burrowing activities of muskrats (from the waterside), as well as voles and gophers (from the landside) advanced the wetting front when burrows intersected (or nearly intersected) the water source. Flow of water through macropores which advanced the wetting front diminished with time. Concentrated seepage mitigation efforts during testing consisting of placing gravel bags over flowing seeps was sufficient to control flows until surrounding soils became saturated and concentrated flows reduced.
The landside tree performed acceptably under saturated conditions and gusting winds conditions, showing a modest rotation of about 0.1 degrees (or about 2 inches measured 6.5 feet up from the base of the tree) based on LiDAR data provided by Gerald Bawden of the USGS. After a little over 39 hours of testing, and the monitoring of a growing seep at the base of the waterside oak tree, the waterside tree rotated approximately 20 degrees and came to rest with the long branch of the tree providing support within the shallow oxbow section of the slough. Cracking and deformation was monitored around the tree, the waterside slope, and the pavement at the crown throughout the duration of the test (Figure 12).

Figure 12. Cracking and seepage locations at the end of the flow test (Time = 245.1 hrs).

Figure 12 shows the location of a cracks that appeared during testing, including a crack between the tree trench and the control trench that appeared less than 3 hours into the flow testing program. The crack continued to grow throughout the first day and began to develop a visible vertical offset about 9 hours into the flow test. Overnight, crack growth continued, reaching a maximum width of just under 0.6 inch and a vertical offset of $\frac{3}{8}$ inch at 13.3 hours
into the flow test (Figure 13). The crack began to close after about 15 hours. This trend continued throughout the remainder of the test, even as the waterside tree fell at 39 hours.

![Graph showing deformation over time](image)

Figure 13. The size of the crack between the tree trench and the control trench was monitored as it grew to a maximum size and then began to get smaller. The crack peaked in size at about 13 hours into the flow test.

In the afternoon of 5/22/12, a little over 25 hours into the flow test, a series of fine cracks opened in the vicinity of instrument Line A, ranging in size from hairline to \( \frac{1}{8} \) inch (Figure 14). The cause of the cracking was not entirely clear and crack monitors did not yield measureable movements. Post-flow, deformations were measured in the pavement with T-LiDAR technology. Subsidence on the order of 1.5 to 6 cm are shown on Figure 14. Largest deformations occurred at a discontinuity in the natural overbank soils, found to be loosely backfilled. Locations of waterside and landside seeps as of test completion are plotted.
MECHANICS OF TREE FAILURE

The failure of the waterside oak was critically examined as follows:

1. The critical turning moment was estimated based on $dbh$ for the waterside oak a correlation presented in Peterson (2012).

2. Tree weights were estimated for the landside and waterside trees using relationships by Myers et al. (1980).

3. Wind forces can add to this destabilization and were estimated based on Peterson (2012) and using a local monitoring station to estimate peak wind velocity as 17.5 m/s during the flow test.

4. Figure 15 shows a diagram by Coutts (1983) explaining the mechanism of tree uprooting under a horizontal force. The diagram was examined to derive a free body diagram of
forces on the root system, presented as Figure 16. The diagram details wind forces, gravitational forces, a reaction force, and root tensile forces extending from a root plate.

5. For the purpose of evaluating tree stability, the size of the root plate was estimated from the empirically derived data associated with windthrow studies.

6. Bond stress for each root was estimated based on embedment, length, and drained friction angle. Pore pressures observed during the flow test resulted in an estimated 40 percent loss in moment resisting capacity in response to pore water pressure accumulation. Assumptions of number of roots with decreasing radius from tree center were made based on root architecture data as discussed below and in Shriro (2014).

7. A number of large roots originating from the waterside oak tree were cut during trenching. The impact of these roots on tree stability was considered using tables of root load capacity with effective stress provided for various root lengths. 10 feet of lost length was assumed, resulting in a reduction of an estimated 9 percent in the capacity of the root system.

8. The result of overturning moment for the waterside tree was compared against resisting moment over the width of the root plate, estimated as the square root of the pit area estimated by Peterson (2012). Original factor of safety against overturning was approximated as 2.0 based on the number of roots, and dropped to 1.0 with the losses associated with cutting roots and increasing pore pressures during the flow test.
Figure 15. Diagram showing (a) the mechanism of overturning and (b) branching. According to Coutts (1983), branching on the leeward side can determine the position of the fulcrum on which the root plate is hinged in overturning.

Figure 16. Free body diagram representing the force balance on the waterside oak tree at Twitchell Island.

GEOSTUDIO SIMULATIONS
An analysis of tree overturning was provided above. The tree was assumed to rotate in the direction of lean, in the downhill direction. Slope stability modeling considers rotation in the
reverse direction. Modeling considered block failures and the lower of the failure mechanisms was assumed. The impact of root reinforcement and tree loading is evaluated as follows:

1. Roots within the root plate are modeled as a rigid body, similar to a footing foundation.
2. Roots extending away from the root plate are modeled as reinforcing elements with zero shear strength in the Slope/W software.
3. Total horizontal and vertical root loading for the waterside oak tree is provided in Table 1.
4. Estimates for number and size of roots at closer distances to the tree are estimated based on available root architecture data (Figure 10) and raw data charts for several valley oak trees excavated by Dr. Alison Berry and Shih-Ming Chung of UC Davis. Roots were estimated to be about 5 times more abundant at distances of 25 to 50 percent of the canopy radius. Roots were about 2.5 times larger at 25 percent of the canopy radius than the size at 50 to 100 percent of the canopy radius. The roots extending from both the waterside and landside oak trees intersected during trenching extend to approximately 65 to 100 percent of the canopy diameter.
5. The horizontal component of force is divided over the ‘slice width’ to arrive at a unit horizontal force and is then further divided to create 5 forces, evenly distributed over the width of the root plate (Table 1, Figure 17). These forces represent the horizontal load on the embankment associated with the lean of the tree and a downhill wind force. Horizontal point loads are only active in the calculation of the factor of safety when included inside the slide circle.
6. Root reinforcement is modeled as a horizontal force acting into the slope, resisting movement. The bonded length of the reinforcement is equal to the length of the reinforcing element outside of the slide zone.

7. The reaction force of the root plate on the levee slope was distributed over the root plate and entered as a unit weight for the root plate within the model. These loads were only applied through the cross section passing through the tree. This cross section is used to represent a ‘slice width’ equal to the square root of the root plate area.

Table 1. Horizontal and vertical root forces waterside oak tree.

<table>
<thead>
<tr>
<th></th>
<th>Total Loads (lbs)</th>
<th>Unit Load (per 1 ft slice) (lbs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T_H (horizontal roots)</td>
<td>74,500</td>
<td>9,300</td>
</tr>
<tr>
<td>T_H25 (inner 25% of canopy radius)</td>
<td>33,500</td>
<td>4,200</td>
</tr>
<tr>
<td>T_H50 (25-50% of canopy radius)</td>
<td>26,100</td>
<td>3,300</td>
</tr>
<tr>
<td>T_H75 (outer 75-100% canopy radius)</td>
<td>14,900</td>
<td>1,900</td>
</tr>
<tr>
<td>T_V (vertical roots)</td>
<td>97,000</td>
<td>12,100</td>
</tr>
</tbody>
</table>

Figure 17. Example of root reinforcing and distributed horizontal forces at the waterside oak.
Coarse-grained soils were considered to be free-draining and were modeled using drained shear strength parameters. Non-free draining materials were modeled under long-term steady state conditions using drained shear strength values correlated from moisture content and index properties, standard penetration test data (SPT), and cone penetration test data (CPT) as discussed in Shriro (2014). Transient and steady state seepage models were generated for the Twitchell Island test site by Cobos et al. (2014) and are not reproduced herein.

FAILURE SCENARIOS AND RESULTS
The three waterside failure scenarios presented on Figure 18, Figure 19, and Figure 20 are modeled under estimated pore water pressure conditions. Waterside failures began with the observation of cracking at just over 2 hours into the flow test, with a crack forming between the control and tree trenches. The failure scenario explored at this location is Waterside BC3 as shown on Figure 18. Scenario Waterside B-2 represents a failure circle at the observed top of slope crack adjacent to the failed waterside oak tree (Figure 19). The levee crown road began to show pavement cracks after about 24 hours of flow in the vicinity of Section A. Stability at this location was explored through modeling of failure scenario Waterside A (Figure 20). Mass-averaged factors of safety against slope instability for modeled scenarios presented on as shown on Table 2. Scenarios Waterside B-2 and BC-3 are modeled with and without the presence of the waterside oak tree.
Figure 18. Waterside failure scenario BC-3.

Figure 19. Waterside failure scenario B-2.
Failure Scenario Waterside B-2 modeled under transient seepage conditions at a time of 39 hours, has factor of safety across the slide mass of 1.16 and 1.03 with and without the waterside oak tree, respectively. For Waterside Failure Scenario BC-3, the calculated mass-averaged factors of safety were 1.72 and 1.67, with and without tree loading, respectively. The presence of the tree results in a small estimated improvement of seepage-induced slope stability, indicating slope deformations observed may have occurred if the waterside tree had not been present, based on poor soil conditions and high pore water pressures induced by the flow test. Mass-averaged factors of safety against slope instability are presented on as shown on Table 2.
CONCLUSIONS AND FUTURE WORK

Flows at the Twitchell Island test site were controlled by macroporosity and stratigraphic conditions related to the presence of an old levee on which the existing levee is founded. Zones of macropores associated with burrowing activities of muskrats (from the waterside), as well as voles and gophers (from the landside) advanced the wetting front when burrows intersected (or nearly intersected) the water source.

At the Twitchell Island test site, three waterside failure scenarios were evaluated. Waterside failure scenarios were defined based on observed cracks visible in the field during the flow test. Each failure scenario was divided into sections and each section given a width and a series of root reinforcement and loading assumptions were implemented. Factors of safety were calculated using mass-averaging of the mass of each slide mass.
Roots were modeled as reinforcing nails with zero shear strength. Portions of the nails that fell within the slide mass were not included in the analysis; yet tree lean and wind forces put a load on these roots that fall within the slide mass. Horizontal forces distributed across the root zone were added such that if these forces fall into the slide mass, they are included in the calculation of factor of safety. Slope stability analyses produced results that showed:

- The Twitchell Island field test landside tree performed acceptably under saturated conditions and gusting wind conditions, showing a modest rotation of about 0.12 degrees (or about 2 inches measured 6.5 feet up from the base of the tree) based on LiDAR data provided by Gerald Bawden of the USGS.

- The presence of a tree had small improvement or little effect on the factor of safety against instability. Factors of safety were nearly identical or slightly higher for the sections with a tree as opposed to those without a tree.

- Nominal pit diameter estimated from windthrow data (Peterson, 2012) is used to approximate the size of the root plate used for distribution of tree loads in slope models, resulting in reasonable results.

- The Twitchell Island field test waterside tree appears to have fallen due to horizontal forces placed on the root system associated with extensive tree lean and wind loading. Saturation of the root system reduced the bond strength on the root system 40 percent.

- Cutting tree roots at the trenches is estimated to have reduced capacity of the root system by approximately 9 percent. Though a smaller effect than that of seepage-
induced instability caused by excess pore pressures induced by the simulated flood condition, this reduction in capacity also contributed to the tree failure.

- The most likely failure scenario for the waterside oak tree is B-2, where the failure scenario extends to the hinge-point of the waterside slope.

Seepage-induced stability does not appear to be largely impacted by the presence of a tree. A small improvement in factor of safety was found in this study. A leaning tree like the waterside oak tree should be evaluated for health of the tree, size, and balance of the tree with consideration to species, soil strengths, benefits to erosion resistance of the levee, consequences of failure, consequences of removal, and other relevant factors specific to each tree. Consideration should be given to other mechanisms of impact to levee integrity, such as erosion following tree failure.

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